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APPLICATION OF KNOWLEDGE-BASED PATTERN RECOGNITION TO MOVEMENT CONTROL OF A GROUP OF VEHICLES

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***Abstract**: The application of knowledge based pattern recognition method for the collision free movement control of a group of vehicles is considered. The control problem consists of two sub–problems: motion control of individual vehicles and traffic control to avoid collisions between moving vehicles. The pattern recognition algorithm is treated as a movement co-ordinator in the second sub–problem. The algorithm makes decisions about the possibility of further movement of vehicles on the basis of features comprising information concerning current states of vehicles. The knowledge for pattern recognition is presented in the form of logical formulae. A multistage approach to pattern recognition is used. It makes the problem less complex. The first sub–problem is solved using the classic control algorithm with local performance index which assures the reaching of the given final positions and velocities. The control algorithm proposed has been tested for three–wheel vehicles using simulation experiments. For this case an example of knowledge representation is given. To determine knowledge based pattern recognition algorithm the logic–algebraic method has been applied. Selected results of those experiments are presented*

Keywords: knowledge-based systems, moving objects, pattern recognition, control systems.

1. Introduction

In the paper the particular problem which concerns the movement control for a group of moving vehicles performing manufacturing on plants located at stationary workstations is investigated. The movement control problem for a single vehicle consists in reaching a given final state for a given initial state to minimise the control performance index. A distributed structure of control system is proposed. While moving in a common working area vehicles can collide or block each other. Therefore it is necessary to co-ordinate their movements. The presentation of a co-ordination algorithm, which makes it possible to avoid collision between vehicles, is the main purpose of the paper. The co-ordination problem treated as a decision making problem is very difficult to formulate analytically and to solve optimally. Therefore, different heuristic and artificial intelligence based approaches are proposed, e.g. [1,5,6,8-12]. In the paper, one of AI based methods is described. It is assumed that an expert is the source of knowledge of collisions and of different conditions for their avoidance. Such knowledge is expressed in the form of logic formulae and the knowledge based pattern recognition problem is solved. The result of the pattern recognition comprises information for the control algorithms of single vehicles as well as about the possibilities of collision free movement in successive control steps. Briefly speaking, this result informs whether the vehicles can safety continue their movement or whether they should stop. In the next two chapters, the problem formulation and the solution algorithm are presented. Then, results of simulation for three-wheel vehicles are given. The simulations conducted allowed us to evaluate the control algorithm.

2. Movement control of the vehicle

Let us consider *R* vehicles, for example Automated Guided Vehicles (AGVs) which are equipped with the same type of driving mechanism. The three wheels driving mechanisms are considered. The front wheel has two degrees of freedom. They make it possible to displace as well as to turn the vehicle. Two rear wheels are fastened to the same axis and have one degree of freedom. The control problem for a single vehicle deals with determination of such control variables that would bring vehicle to a given position and velocity. The initial position and the initial velocity are known. Moreover, the movement should be collision–free with respect to stationary and moving obstacles.

2.1. Model of the vehicle

The driving mechanism being the control plant is treated as a rigid body. No friction forces are considered and it is assumed that the total mass is concentrated at one point, i.e. over the axis of the front wheel. As control variables for the vehicle r, $r = 1,2,\ldots,R$, torques $u_r^{(1)}(t)$ and $u_r^{(2)}(t)$ have been assumed. They cause the linear displacement and the turn, respectively and form the vector

$$u_r(t) = [u_r^{(1)}(t), u_r^{(2)}(t)]^{\mathrm{T}}.$$

The position of the vehicle is described in Cartesian co-ordinate system. It is enough to consider two variables: the point corresponding to the axis of the front wheel as well as the angle between the axis of vehicle and the abscissa of the co-ordinate system. Two points that correspond to the front wheel and the middle of the axis of rear wheels determine the axis of vehicle. After taking into account an angle which describes the turn of the front wheel, the following set of coordinates makes up the unique description of the position of the control plant under consideration (Fig.1)

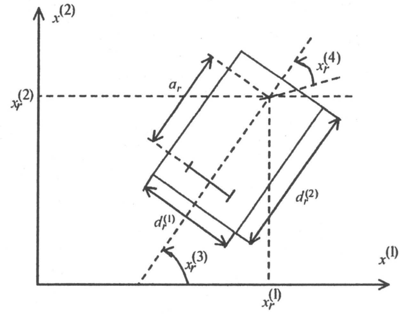

Fig.1. Projection of driving mechanism of vehicle r with state variables and dimensions $d_r^{(1)}$, $d_r^{(2)}$

$x_r^{(1)}, x_r^{(2)}$ – co-ordinates of the front wheel in Cartesian system,

$x_r^{(3)}$ – angle between the abscissa and the axis of vehicle,

$x_r^{(4)}$ – angle of turn, i.e. the angle between the axis of vehicle and the plane of the front wheel.

Another quantity which is very important for description of the movement of control plant (the rth vehicle) is velocity. Because of two movements performed by the plant, two velocities denoted by $x_r^{(5)}$ and $x_r^{(6)}$ may be distinguished, i.e. linear displacement velocity and the velocity of turn, respectively. The positions and the velocities, which have been introduced, allow us to formulate the state vector $\boldsymbol{x}_r = [x_r^{(1)}, x_r^{(2)}, x_r^{(3)}, x_r^{(4)}, x_r^{(5)}, x_r^{(6)}]^{\mathrm{T}}$. The state equations are derived based on simple geometric considerations and using kinematic energy of the plant. Then

$$\dot{x}_r^{(1)}(t) = x_r^{(5)}(t)\cos[x_r^{(3)}(t) - x_r^{(4)}(t)], \quad (1)$$

$$\dot{x}_r^{(2)}(t) = x_r^{(5)}(t)\sin[x_r^{(3)}(t) - x_r^{(4)}(t)], \quad (2)$$

$$\dot{x}_r^{(3)}(t) = -\frac{1}{a_r} x_r^{(5)}(t) \sin[x_r^{(4)}(t)], \tag{3}$$

$$\dot{x}_r^{(4)}(t) = x_r^{(6)}(t), \tag{4}$$

$$\dot{x}_r^{(5)}(t) = \frac{1}{m_r \rho_r} u_r^{(1)}(t), \tag{5}$$

$$\dot{x}_r^{(6)}(t) = \frac{1}{J_r} u_r^{(2)}(t), \tag{6}$$

where a_r – distance between axes of vehicle r (Fig.1), m_r – total mass of vehicle r, ρ_r – radius of front wheel, J_r – moment of inertia of the front wheel. Equations (1)–(6) and the initial state

$$\boldsymbol{x}_{r,0} = [x_{r,0}^{(1)}, x_{r,0}^{(2)}, x_{r,0}^{(3)}, x_{r,0}^{(4)}, x_{r,0}^{(5)}, x_{r,0}^{(6)}]^{\mathrm{T}},$$

where $x_{r,0}^{(i)} \triangleq x_r^{(i)}(\underline{t})$, $i = 1,2,\ldots,6$ and $\underline{t}$ is the moment when the motion starts, form the mathematical model of the control plant.

2.2. Problem formulation

A discrete version of state equations (1)–(6) is used in the form of the following difference equations

$$x_{r,\nu+1}^{(i)} = f_r^{(i)}(x_{r,\nu}, u_{r,\nu}), \; i = 1,2,\ldots,6, \; \nu = 0,1,\ldots, \tag{7}$$

where $x_{r,\nu}^{(i)} \triangleq x_r^{(i)}(t = \nu h)$, $i = 1,2,\ldots,6$, $u_{r,\nu}^{(i)} \triangleq u_r^{(i)}(t = \nu h)$, $i = 1,2$. The variables ν and h denote the index of control step and the length of control step, respectively.

Equations (7) are results of discretisation of functions $x_r^{(i)}(t)$. The corresponding calculations are omitted.

From the point of view of the problem under consideration very important are constraints imposed on control variables and especially on state variables. Most of them are in the form of intervals, i.e.

$$u_r^{(i)}(t) \in [\underline{u}_r^{(i)}, \overline{u}_r^{(i)}], \; i = 1,2, \tag{8}$$

$$x_r^{(i)}(t) \in [\underline{x}_r^{(i)}, \overline{x}_r^{(i)}], \; i = 4,5,6, \tag{9}$$

where the ends of intervals are given values.

The state variable $x_r^{(3)}$ is not constrained. Such a form of constraints cannot be assumed for $x_r^{(1)}$ and $x_r^{(2)}$ because the admissible zone for any vehicle is not a rectangle. It is denoted by $\boldsymbol{Y}_{r,v}$ and has the form

$$\boldsymbol{Y}_{r,v} = \{(x_{r,v}^{(1)}, x_{r,v}^{(2)}) : (x_{r,v}^{(1)}, x_{r,v}^{(2)}) \in \boldsymbol{X}^{(1)} \times \boldsymbol{X}^{(2)} - (\bigcup_{\substack{s=1 \\ s \neq r}}^{R} \boldsymbol{D}_{s,v} \cup \bigcup_{g=1}^{G} \overline{\boldsymbol{D}}_g)\}, \tag{10}$$

where $\boldsymbol{X}^{(i)} \triangleq [\underline{x}_r^{(i)}, \overline{x}_r^{(i)}]$, $i = 1,2$ – given intervals which define the working area for vehicles, $\boldsymbol{D}_{s,v}$ – area occupied by vehicle s in control step v (forbidden area), $\overline{\boldsymbol{D}}_g$ – area occupied by stationary obstacle g, G – number of stationary obstacles.

The areas $\overline{\boldsymbol{D}}_g$ are given a priori and zones $\boldsymbol{D}_{s,v}$ are determined during the control procedure.

A "point–to–point" strategy is proposed for determination of the control algorithm. It consists in derivation of such a control vector $\boldsymbol{u}_{r,v} = [u_{r,v}^{(1)}, u_{r,v}^{(2)}]^{\mathrm{T}}$ that would minimise in the current control step v the distance between current position and the position given by $x_r^{*(1)}$ and $x_r^{*(2)}$. The algorithm allows us also to obtain the orientation according to $x_r^{*(3)}$ and velocities given by $x_r^{*(5)}$ and $x_r^{*(6)}$. The requirements are grouped in the vector $\hat{\boldsymbol{x}}_r = [x_r^{*(1)}, x_r^{*(2)}, x_r^{*(3)}, x_r^{*(5)}, x_r^{*(6)}]^{\mathrm{T}}$, which is a sub-vector of the final state $\boldsymbol{x}_r^* = [x_r^{*(1)}, x_r^{*(2)}, \ldots, x_r^{*(6)}]^{\mathrm{T}}$.

The following local performance index results from those requirements

$$q_{r,\nu}(\boldsymbol{u}_{r,\nu}) = \sum_{i\in\{1,2,5,6\}} \alpha_i [x_r^{*(i)} - f_r^{(i)}(\boldsymbol{x}_{r,\nu}, \boldsymbol{u}_{r,\nu})]^2 + \alpha_3 [\beta_{r,\nu} - \sum_{i\in\{1,2\}} (-1)^{i+1} \cdot f_r^{(i)}(\boldsymbol{x}_{r,\nu}, \boldsymbol{u}_{r,\nu})]^2, \tag{11}$$

where α_i, $i = 1,2,3,5,6$ – non–negative coefficients, $\beta_{r,\nu}$ – angle between the line which contains points $(x_{r,\nu}^{(1)}, x_{r,\nu}^{(2)})$, $(x_r^{*(1)}, x_r^{*(2)})$ and the abscissa.

It is necessary to introduce the stop condition. The following form is obtained

$$\left(\sum_{i\in\{1,2,3,5,6\}} (\hat{x}_r^{(i)} - x_{r,\nu}^{(i)})^2 \right)^{1/2} \le \varepsilon_r \tag{12}$$

with ε_r being the accuracy of reaching the final state.

Now, one can formulate the motion control problem for the rth vehicle. Given: model (7) with initial state $x_{r,0}$, admissible zones $\boldsymbol{Y}_{r,\nu}$, $\nu = 0,1,2,\ldots$, requirements $\hat{\boldsymbol{x}}_r$ for the determination of the movement, coefficients α_i, $i = 1,2,3,5,6$ as well as accuracies ε_r, determine: the sequence of control vectors $(\boldsymbol{u}_{r,\nu})_{\nu=0,1,2,\ldots}$ admissible in the sense of (8)–(10) to minimise (11) until the stop condition (12) is fulfilled.

The forms of $\boldsymbol{Y}_{r,\nu}$ force the application of an adequate numerical procedure while solving the optimisation problem formulated.

3. Co-ordination of the movement

Let us return to the basic problem under consideration, i.e. to motion control of R vehicles. For any vehicle it is necessary to avoid collisions with stationary and moving obstacles. Therefore, it is not enough to solve R optimisation problems, which have been introduced in chapter 2. The zones $\boldsymbol{Y}_{r,\nu}$ can be treated as co–ordination variables, which connect local control algorithms for individual vehicles. The two–level control algorithm, with determination of zones $\boldsymbol{D}_{s,\nu}$ and consequently of zones $\boldsymbol{Y}_{r,\nu}$ has been introduced in [3]. Now, another approach to co–ordination of local control algorithms will be presented. It also requires a two–level structure of control system (Fig.2) but with knowledge–based pattern recognition at the upper level.

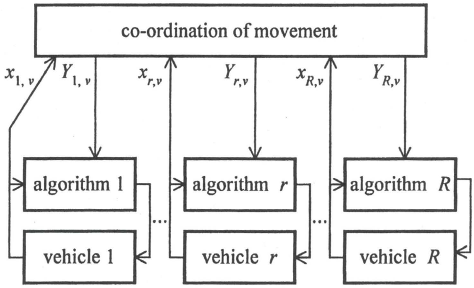

Fig.2. Two–level structure of control system with state vectors $x_{r,v}$ and admissible areas for vehicles $Y_{r,v}$

3.1. Co-ordination algorithm

The co-ordination algorithm is proposed in the form of knowledge based pattern recognition. As the basis for the recognition, simple formulae are considered. They are derived taking into account information from states $x_{r,v}$. Let $\alpha_x^r = (\alpha_{x1}^r, \alpha_{x2}^r, ..., \alpha_{xg_r}^r)$ be the sequence of simple formulae concerning vector $x_{r,v}$ for the rth vehicle and $\alpha_x^{r,s} = \left(\alpha_{x1}^{r,s}, \alpha_{x2}^{r,s}, ..., \alpha_{xg_{r,s}}^{r,s}\right)$ – the corresponding sequence concerning $x_{r,v}$ and $x_{s,v}$ for the pair of current vehicles (r,s). Moreover, $\alpha_x = (\alpha_x^r, \alpha_x^{r,s})_{\substack{r,s=1,2,...,R \\ r \neq s}}$ is the sequence of simple formulae for all vehicles and for all pairs of vehicles. The following result of recognition denoted by j_r can be chosen: $j_r = 1$ – vehicle r can move, $j_r = 2$ – vehicle r can move with collision avoidance, $j_r = 3$ – movement of vehicle r has been finished, $j_r = 4$ – vehicle r should stop to avoid collision. Let $j_r \in J_r = \{1,2,3,4\}$. The sequence $(j_1, j_2, ..., j_R)$ is the result of recognition for all vehicles. The set of all classes is denoted by $J = \{1,2, ..., M\}$, where $M = 4^R$ is the number of classes. The class $j \in J$ is easy to derive using the sequence $(j_1, j_2, .., j_R)$, i.e. $j = 1 + \sum_{r=1}^{R} 4^{r-1}(j_r - 1)$. Additionally, let $\alpha_{ji}^r = "j_r = i"$, $i = 1,2,3,4$ be the simple formula for class j_r, $\alpha_j^r = (\alpha_{j1}^r, \alpha_{j2}^r, \alpha_{j3}^r, \alpha_{j4}^r)$ and $\alpha_D = (\alpha_j^1, \alpha_{j2}^2, ..., \alpha_j^R)$. The sequence α_D together with α_x is used for determination of k facts $F_i(\alpha_x, \alpha_D)$, $i = 1,2,...,k$ being logical expressions. All facts are true and form knowledge representation $F = F_1 \wedge F_2 \wedge ... \wedge F_k$.

Then the pattern recognition problem can be stated as follows. Given: features (results of measurements) in the form of fact $F_x(\alpha_x)$, knowledge representation $F(\alpha_x, \alpha_D)$, determine: the minimum set $D_j \subseteq J$ to make the following implication $F_x(\alpha_x) \wedge F(\alpha_x, \alpha_D) \rightarrow j \in D_j$ true.

The logic–algebraic method ([2]) is proposed for solving the problem. Consequently, the equation $F_x(a_x) \wedge F(a_x, a_D) = 1$ in Boolean algebra is to be solved with respect to a_D. As a result the set

$$\overline{S}_D = \left\{ a_D \in S_D : \bigvee_{a_x \in S_x} F_x(a_x) \wedge F(a_x, a_D) = 1 \right\}$$

is obtained, where S_x and S_D are the sets of all a_x and a_D, respectively. The solution is expressed in the form

$$D_j = \left\{ j \in J : \bigvee_{a_D \in \overline{S}_D} j = 1 + \sum_{r=1}^{R} \left(\sum_{i=1}^{4} n a_{ji}^r - 1 \right) 4^{r-1} \right\}.$$

To solve the pattern recognition problem formulated a decomposition procedure, called multistage pattern recognition, has been applied. Now, only a general description is given. More details can be found e.g. in [7,4]. At successive recognition stages the decisions are made concerning the subsets of possible classes and features, which are used at the next level. The decision at the nth level ($n = 1,2, ..., N = R(R-1)/2$) comprises the determination of subset $D_j^n \subseteq J$. The subset D_j^N is the final result of recognition. The application of multistage pattern recognition consists in determination of the state of a possible collision for two vehicles r and s. The effective co-ordination requires the verification of this state for each pair of vehicles. To avoid the deadlock the priority in the set of vehicles has been introduced. The vehicle with lower number has higher priority. A block scheme of multistage pattern recognition is given in Fig.3. The logic expressions $F_x^{r,s}(\alpha_x^r, \alpha_x^s, \alpha_x^{r,s})$ and

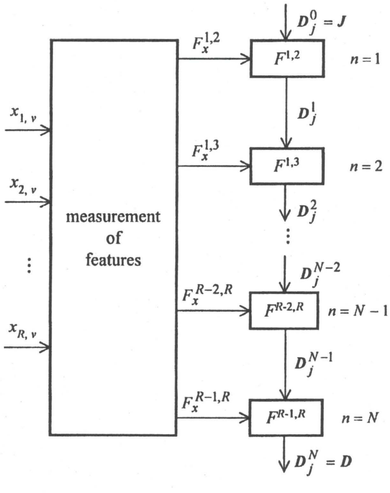

Fig.3. Multistage pattern recognition for vth control step

$F^{r,s}(\alpha_x^r, \alpha_x^s, \alpha_x^{r,s}, \alpha_j^r, \alpha_j^s)$ denote the features and knowledge representation for the respective vehicles.

3.2. Knowledge representation for the *n*th pattern recognition stage

In further investigations the following simple formulae concerning features are used:

1. $\alpha_{x,1}^{r,s} = \sqrt{\sum_{i=1}^{2}(x_{r,v}^{(i)} - x_{s,v+1}^{(i)})^2} < d$,

2. $\alpha_{x,2}^{r,s} = \sqrt{\sum_{i=1}^{2}(x_{r,v+1}^{(i)} - x_{s,v}^{(i)})^2} < d$,

3. $\alpha_{x,3}^{r,s} = \sqrt{\sum_{i=1}^{2}(x_{r,v+1}^{(i)} - x_{s,v+1}^{(i)})^2} < d$,

4. $\alpha_{x,4}^{r,s} = \pi - \theta < \left|x_{r,v}^{(3)} - x_{s,v}^{(3)}\right| < \pi + \theta$,

5. $\alpha_{x,1}^{r} = \sqrt{\sum_{i=1}^{2}(x_{r,v}^{(i)} - \hat{x}_{r}^{(i)})^2} < \varepsilon_r$,

6. $\alpha_{x,1}^{s} = \sqrt{\sum_{i=1}^{2}(x_{s,v}^{(i)} - \hat{x}_{s}^{(i)})^2} < \varepsilon_s$.

Variables $x_{r,v+1}$ and $x_{s,v+1}$ denote prospective states for executors. The parameter d is the safe distance between executors. The second parameter θ describes the directions of movements of vehicles. If the angle between these directions is less than θ then intermediate states should be determined to avoid collision. Otherwise, for the collision avoidance it is enough to stop the movement of the vehicle with lower priority.

The following facts, i.e. knowledge representation have been assumed for the case of two vehicles:

$$F_1^{r,s} = \alpha_{x,1}^{r} \rightarrow \alpha_{j,3}^{r},$$

$$F_2^{r,s} = \neg\alpha_{x,1}^{r} \rightarrow (\alpha_{j,1}^{r} \vee \alpha_{j,2}^{r} \vee \alpha_{j,4}^{r}),$$

$$F_3^{r,s} = (\alpha_{x,1}^{r,s} \vee \alpha_{x,2}^{r,s} \vee \alpha_{x,3}^{r,s}) \wedge (\alpha_{x,4}^{r,s} \vee \alpha_{j,4}^{s}) \rightarrow (\alpha_{j,2}^{r} \vee \alpha_{j,4}^{r}),$$

$$F_4^{r,s} = \alpha_{x,1}^s \rightarrow \alpha_{j,3}^s,$$

$$F_5^{r,s} = \neg\alpha_{x,1}^s \rightarrow (\alpha_{j,1}^s \vee \alpha_{j,2}^s \vee \alpha_{j,4}^s),$$

$$F_6^{r,s} = (\alpha_{j,1}^r \vee \alpha_{j,2}^r) \wedge (\alpha_{x,1}^{r,s} \vee \alpha_{x,2}^{r,s} \vee \alpha_{x,3}^{r,s} \vee \alpha_{x,4}^{r,s}) \rightarrow (\alpha_{j,2}^s \vee \alpha_{j,4}^s),$$

$$F_7^{r,s} = (\alpha_{j,1}^r \wedge \neg\alpha_{j,2}^r \wedge \neg\alpha_{j,3}^r \wedge \neg\alpha_{j,4}^r) \vee (\neg\alpha_{j,1}^r \wedge \alpha_{j,2}^r \wedge \neg\alpha_{j,3}^r \wedge \neg\alpha_{j,4}^r)$$
$$\vee (\neg\alpha_{j,1}^r \wedge \neg\alpha_{j,2}^r \wedge \alpha_{j,3}^r \wedge \neg\alpha_{j,4}^r) \vee (\neg\alpha_{j,1}^r \wedge \neg\alpha_{j,2}^r \wedge \neg\alpha_{j,3}^r \wedge \alpha_{j,4,}^r),$$

$$F_8^{r,s} = (\alpha_{j,1}^s \wedge \neg\alpha_{j,2}^s \wedge \neg\alpha_{j,3}^s \wedge \neg\alpha_{j,4}^s) \vee (\neg\alpha_{j,1}^s \wedge \alpha_{j,2}^s \wedge \neg\alpha_{j,3}^s \wedge \neg\alpha_{j,4}^s)$$

$$\vee (\neg\alpha_{j,1}^s \wedge \neg\alpha_{j,2}^s \wedge \alpha_{j,3}^s \wedge \neg\alpha_{j,4}^s) \vee (\neg\alpha_{j,1}^s \wedge \neg\alpha_{j,2}^s \wedge \neg\alpha_{j,3}^s \wedge \alpha_{j,4}^s).$$

Facts $F_1^{r,s}$ and $F_2^{r,s}$ comprise conditions for finishing and further movement for vehicle r, respectively. The analogous conditions for vehicle s are given in facts $F_4^{r,s}, F_5^{r,s}$. In facts $F_3^{r,s}$ and $F_6^{r,s}$ the collision avoidance conditions are described. Facts $F_7^{r,s}$ and $F_8^{r,s}$ ensure the determination of a single class during pattern recognition procedures.

4. Simulation experiments

The simulation has been conducted for three-wheel vehicles with the model given in chapter 2. For simulation, evaluation and testing of the control algorithm with knowledge-based pattern recognition a computer program has been developed. An example of its performance is presented in Fig.4. The effectiveness of the algorithm and the time of the movement have been evaluated. The following performance indices have been used

$$\delta_{\mathrm{N}} = N_f / N,$$

where N_f – number of invalid performances of the algorithm, i.e. number of cases where the final state has not been reached, N – number of all performances of the algorithm as well as

$$\delta_{\mathrm{I}} = I,$$

where I – number of control steps (iterations of the control algorithm). Examples of simulation experiments are presented in Figs. 5, 6 and 7.

The results presented are the average values, which have been obtained for 1000 different cases, i.e. for 1000 randomly generated pairs of states $(x_{r,0}, x_r^*)$. The result from Fig.5 shows that the influence of the safe distance d on the effectiveness of the control algorithm is almost linear and its increasing does not make the control algorithm better. Very similar forms of dependence can be observed in Fig.6 and in Fig.7, i.e. the greater the h and $\bar{u}^{(1)} = \bar{u}_1^{(1)} = \bar{u}_1^{(2)}$ the shorter is the time of movement. The tests of the control algorithm via computer simulation confirmed its usefulness and possibilities of its application to real moving facilities.

5. Final remarks

In the paper, the new idea for the co-ordination of collision-free movement of a group of vehicles is presented. The knowledge-based pattern recognition is applied as the co-ordination algorithm. For solving the complex problem of pattern recognition the decomposition in the form of multistage procedure is used. The evaluation of the control algorithm has been performed only for three-wheel vehicles. Further investigations will be focused on the cases with greater number of moving vehicles. The application of other AI based methods is considered too. It also concerns the movement control of a single vehicle.

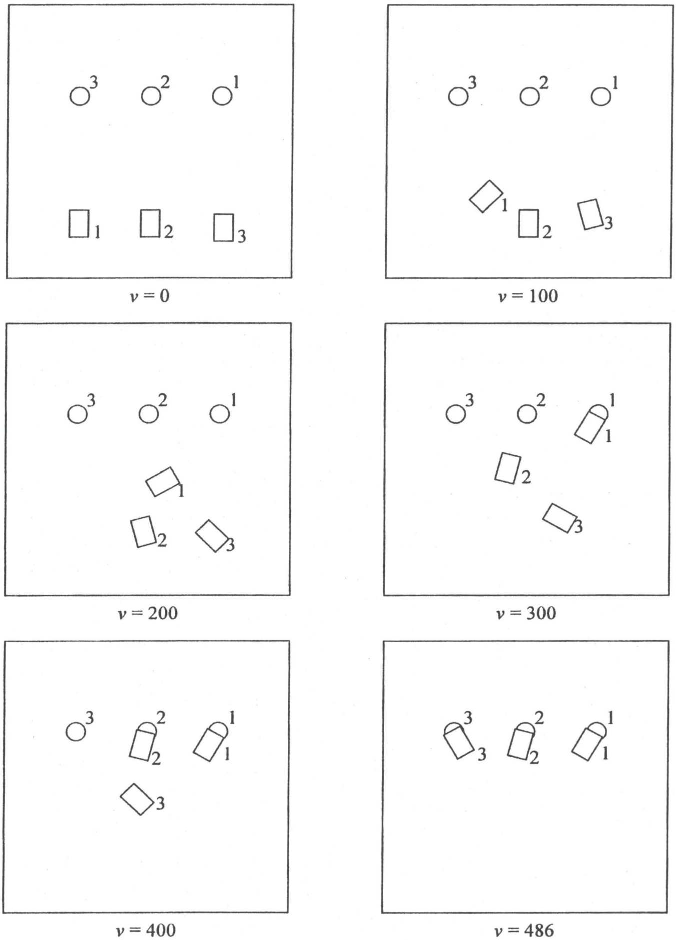

Fig.4. Example performance of the computer testing procedure with three–wheel vehicles for different number of control steps v ($I = 486$)

Instead of the classical control algorithm, the fuzzy-. logic control algorithms can be used. This would enable us to omit the complex model of vehicles, which even for serious simplifications, like in the paper, is rather complicated and makes the control of vehicles movement difficult and time consuming. For fuzzy-logic approach, it is enough to use only the rules given by an expert but their quality and reliability are crucial The application of this approach in connection with knowledge-based pattern recognition leads to the full AI based control system for a group of moving vehicles.

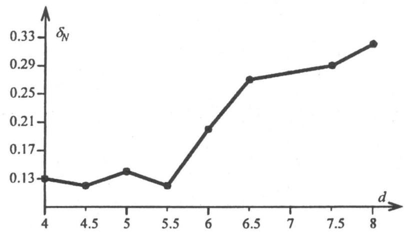

Fig.5. Dependence of δ_N on d

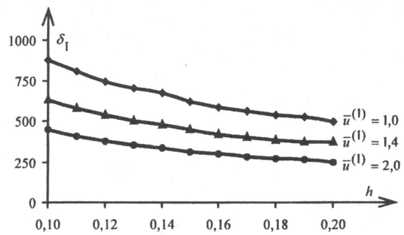

Fig.6. Dependence of δ_I on the length of control step h for different values of maximum linear velocity $\bar{u}^{(1)}$

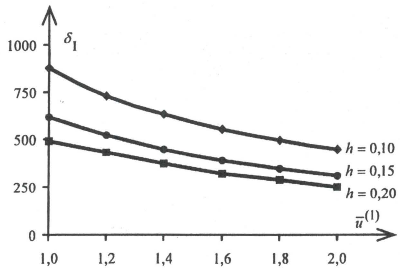

Fig.7. Dependence of δ_I on $\bar{u}^{(1)}$ for different h

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